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Flicker attenuation and transfer study for induction generator integrated into distribution network

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ABSTRACT

Squirrel-cage induction generators (IGs) are widely used in distributed generation (DG). When the voltage at the point of common coupling is fluctuant, the embedded IG will show the impedance characteristic with dynamic changes under the different fluctuation frequencies. In addition, the drive train of IG set has great impact on the voltage flicker attenuation. This paper observes the dynamic response of IG to the voltage flicker through the experiments and further defines the flicker attenuation factor and transfer coefficient. A linearization model of IG with two-mass equivalent drive train is constructed through comparing the impacts of different drive trains (such as diesel engine, wind turbine) on the voltage flicker attenuation. Then an analytical method is proposed to determine the dynamic impedance, attenuation factor, transfer coefficient and flicker limit for IG integrated into distribution network. The correctness of the proposed method is verified by the experimental tests and the dynamic simulation using the detailed model of IG set. The parameters sensitivities of drive train and generator to the voltage flicker attenuation effect are analyzed and discussed in the paper.

1. Introduction

Voltage fluctuation leading to voltage flicker caused by fluctuating loads and sources in distribution network tends to propagate in grid with some levels of attenuation [1,2]. The attenuation is a function of loads and sources impedances, which can be described by the flicker transfer coefficient [3]. With the development and utilization of renewable power, a variety of distributed generations begin to be embedded in utility grid. Distributed generators include synchronous generators, induction generators and other power sources with the electronic interface. Compared with the synchronous generators, squired-cage rotor induction generators are widely used due to the advantages of low cost and easy maintenance and so on [4,5]. The rotor linkage of IG will be fluctuant followed by the voltage fluctuation at the point of common coupling (PCC), leading dynamic changes to impedance characteristic with different fluctuation frequencies. The attenuation process of IG determines the flicker transfer in power grid directly. The calculation of the transfer coefficient is vital for the evaluation of flicker emission as well as the determination of flicker limitation and suppression measures.

Flicker transfer coefficient is measured and analyzed by a synchronous flicker measure device in Refs. [6,7]. The simulation in time-domain is developed to calculate the coefficient for each node [3]. The propagating of the flicker caused by the integration of DG into the distribution network depends on several factors including short-circuit capacity of grid, voltage fluctuation frequencies as well as the dynamic impedance of fluctuated sources and loads [3,8–10]. Ref. [3] addressed the frequency feature of the dynamic impedance of the synchronous generator. It proposed an algorithm of the dynamic impedance based on the state equations, which can obtain accurate result of flicker transfer in distribution grid. The flicker attenuation characteristic of inductor motor loads is analyzed by Ref. [8] when a balanced single-frequency component or a sinusoidal amplitude modulated wave is superimposed on the mains voltage. Furthermore, Ref. [9] proposed an accurate algorithm of flicker transfer coefficient for the grid containing induction motor (IM) loads. Nevertheless, the transient state impedance and steady state impedance of IG are often used for the flicker analysis [10,11], without considering the dynamic feature, which cannot announce the frequency dependence of flicker transfer coefficient. The dynamic characteristics of IG to voltage flicker are demonstrated in Ref. [12], but the work does not consider the effect of distribution grid on its stator voltage response and cannot provide the solution of flicker transfer coefficient for distribution grid with IG. It is reported that IG will contribute toward

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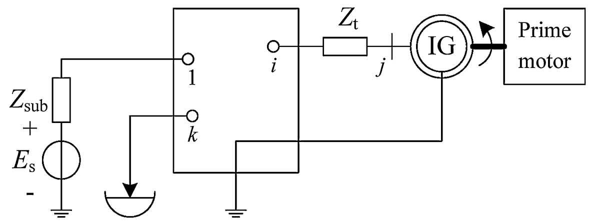

Fig. 1. Equivalent circuit of IG in grid.

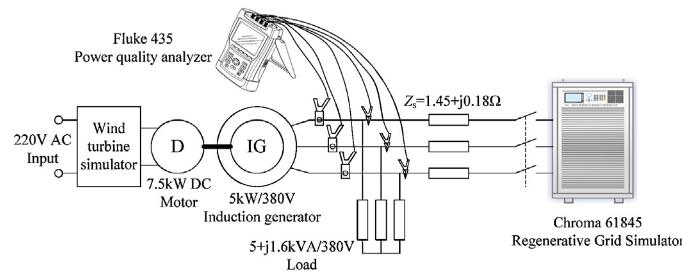

Fig. 3. Laboratory setup for voltage flicker measurement.

attenuating the flicker in grid. However, the phenomenon has not been confirmed by the experimental tests. On the other hand, the drive trains between IG and IM are different. Especially the flexibility of the drive train has significant influence to the power of induction machine [13]. This paper is an extension of our preliminary survey in Ref. [12]. The stator current and terminal voltage responses of IG to flicker are studied by the experiment of a distribution network with IG, and then the impact of the drive train of IG set on its flicker dynamic responses is analyzed. To determine the dynamic impedance, attenuation factor, transfer coefficient and the flicker limit of PCC voltage, an analytical method is proposed based on the linearization model with two-mass equivalent drive train to develop the previous study. The proposed technique is verified through using the experimental test and the dynamic simulation software MATLAB/Simulink where IG set is presented by the seventh-order model.

2. Dynamic response of induction generator to voltage flicker

The equivalent circuit of IG integrated into grid is shown in Fig. 1. The generator set is connected in node i through the transformer, where Z_t stands for the short-circuit impedance of the transformer. Node k has typical fluctuant loads or sources, and the load current is assumed as $i_k = i_{k0} + \Delta i_k$. Thus, the Thevenin equivalent circuit [14] of node i can be obtained and shown in Fig. 2, where the internal impedance is equal to the self-impedance Z_{ii}, and the equivalent potential is the open-circuit voltage of node i, which is u_{ioc}. Suppose u_{ioc} is the sinusoidal amplitude modulated given by

$$u_{ioc}(t)|_{a,b,c} = U_p[1 + m\sin(2pf_m t)]\cos\left[2pf_n t - (n-1)\frac{2p}{3}\right] = U_p\cos[2pf_n t - (n-1)] - \frac{m}{2}U_p\sin\left[2p(f_n - f_m)t - (n-1)\frac{2\pi}{3}\right] + \frac{m}{2}U_p\sin\left[2p(f_n + f_m)t - (n-1)\frac{2\pi}{3}\right] \quad (1)$$

where $n = 1, 2, 3$ stands for a, b, c three phases; U_p is the peak value of mains voltage; m is the modulation depth; $f_n = 50$ Hz is the mains frequency and f_m is modulation frequency ranging from 0.05 Hz to 35 Hz.

This modulated voltage contains a pair of positive-sequence interharmonic components with the frequencies $f_n - f_m$ and $f_n + f_m$, respectively, namely $u_{ioc} = u_{ioc}^{f_n} + \Delta u_{ioc}^{f_n - f_m} + \Delta u_{ioc}^{f_n + f_m}$. An experiment platform is built to test the dynamic response of IG to voltage flicker. The laboratory setup is shown in Fig. 3, where a 5 kW IG driven by DC motor is operated in torque control mode to simulate a wind turbine. The modulated voltage is generated by a Chorma61845 regenerative grid simulator. It could provide the excitation for IG starting, and sense the excess power and recycle it back to the grid when the output power of IG is beyond the local load. The voltage flicker and current harmonic is measured by a Fluke435 power quality analyzer.

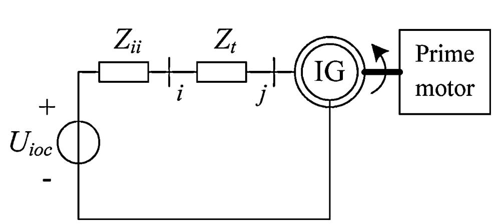

Fig. 2. Thevenin equivalent circuit of node i.

The test results of stator current and terminal voltage of a 5 kW IG to the voltage flicker are shown in Fig. 4. As the A-phase current of IG shown in Fig. 4(a) where the condition of modulated voltage is $m = 0.6\%$, $f_m = 5$ Hz, the modulated voltage leads to a cyclical fluctuation in the peak value of stator current. There are two extreme points with the frequencies 45 Hz and 55 Hz in the frequency spectra of current corresponding to the interharmonic components of voltage at $f_m = 5$ Hz. The IG will inject the interharmonic currents with different magnitudes according to its response characteristics changing with the frequencies.

In Fig. 4(b), the instantaneous flicker sensation P_{ins} at $f_m = 5$ Hz and the short-term flicker severity P_{st} versus f_m are measured, respectively, over 1 s and 10 min by the power quality analyzer. P_{st} is calculated by the statistical analysis of P_{ins} [15]. From $t = 0$–20 s, the IG accelerates to the rated speed. At $t = 20$ s, the power supply changes to the modulated voltage source. P_{ins} of IG during the starting process is lower than that of the status with modulated voltage after $t = 20$ s. When the IG is replaced with a passive load, P_{ins} picks up noticeably where the modulated voltage enables during the whole test period. As shown by the ratio between P_{st} of IG and passive load in Fig. 4(b), the connection of IG decreases P_{st} of the local load's voltage from $f_m = 0.6$ Hz to 35 Hz. The experimental results indicate the flicker propagated to the load at IG terminal attenuates because of its dynamic current (or impedance) response.

3. Flicker attenuation factor and transfer coefficient

3.1. Flicker attenuation factor

The flicker severity is proportional to its relative voltage change [6–10]. The voltage fluctuation of IG propagated from the mains voltage can be obtained by Eq. (2) where the generator uses its steady state impedance $Z_{ig}(f)$ and the system impedance $Z_s(f)$ is assumed as $Z_{ii}(f) + Z_t(f)$, in which the reactance value of Z_s and Z_{ig} is linear with frequency.

$$\Delta u_j = \frac{Z_{ig}(f_n - f_m)\Delta u_{ioc}^{f_n - f_m}}{Z_s(f_n - f_m) + Z_{ig}(f_n - f_m)} + \frac{Z_{ig}(f_n + f_m)\Delta u_{ioc}^{f_n + f_m}}{Z_s(f_n + f_m) + Z_{ig}(f_n + f_m)} = \eta_{ig}(f_n - f_m)\Delta u_{ioc}^{f_n - f_m} + \eta_{ig}(f_n + f_m)\Delta u_{ioc}^{f_n + f_m} \quad (2)$$